LCA Case Studies

LCA of Electronic Products

An environmental assessment of Gallium Arsenide Monolithic Microwave Integrated Circuit System-In-a-Package (SIP) Switch Product

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Abstract

Intention, Goal, Scope, Background. A new paradigm called System-In-a-Package (SIP) is expected to represent the wave of future microsystem packaging and integration. No environmental assessment has been made of manufacturing processes for SIP and the purpose of this paper is to assess the upstream environmental impact of the process used by Chalmers to manufacture an electronic product using the SIP technology.

Objectives. This paper aims at an environmental assessment of a gallium arsenide (GaAs) Monolithic Microwave Integrated Circuit (MMIC) Switch Product based on a so-called SIP concept on a Liquid Crystalline Polymer (LCP) substrate. This study focuses on the identification of environmentally substantial upstream processes from cradle-to-gate for this product.

Methods. This work is based on a life cycle inventory model that has been developed earlier by the authors, and this model is now applied to the system including the straight-line manufacturing processes in the facilities of the Microtechnology Centre (MC2) at Chalmers University of Technology and the manufacturing processes of raw materials in the upstream processes. A main scenario was built in the LCA software EcoLab corresponding to the linear process in MC2 and other manufacturing processes were identified in the upstream which were used to develop the upstream process tree.

Results and Discussion. The spin coating of photoresistant material has the highest environmental impact within the system boundaries and the uncertainty of the results is estimated to be small. The exposure and development as well as deposition stages also give impacts, both for the copper and resistant material deposition. In the manufacturing processes inside MC2, the electricity consumption clearly dominates. The results predominantly reflect energy use, whereas toxicological aspects could not be reliably assessed due to lack of data and reliable methods, and therefore needs separate attention. Nevertheless, a toxicology assessment has been made with the Toxic Potential Indicator (TPI), which, compared to a telephone, showed a relatively large value for the switch. The toxic potential of the switch is higher per mass unit than a digital telephone.

Conclusions. The previously developed LCA data collection model worked well for the SIP product. The electricity consumption for the deposition machine and the solvent consumption in spin coating are the two most important hot spots. For greenhouse warming potential the acetone consumption in the spin coating steps is the most significant contributor, and the copper consumption in the copper deposition step dominates for abiotic resource depletion.

Recommendations and Outlook. It is recommended that the machines in the MC2 process lab used to manufacture the SIP product are studied for a longer period of time as it would make the electricity consumption figures more accurate. More electronic packaging concepts, such as System-on-a-chip (SOC) and multichip modules (MCM), should be evaluated and compared to SIP.

Keywords: Eco-indicator; electronic products; environmental assessments; gallium arsenide; LCI methodology; life cycle assessment (LCA); life cycle inventory (LCI); liquid crystalline polymer (LCP); monolithic microwave integrated circuit switch; system-in-a-package (SIP); upstream processes

Introduction

A new paradigm called System-In-a-Package (SIP) is expected to represent the wave of future microsystem packaging and integration. SIP is a single component, multi-functional, multi-chip package providing all the needed system functions. In the 21st century, the new challenge is not how many transistors can be built onto a single chip, but how to integrate these together predictably, harmoniously and cost effectively. Designers hope to merge memory with logic, mixed signals with digital signals, and to integrate passive components with active circuits, but this complexity will increase the cost of the manufacturing process as the options include integrated circuits and passive components packaged together in a functional module. It is a new development and provides an extension of today's system packaging and integration, driven by the emerging low cost, low parasitic packaging technologies, particularly for portable, low power consumption and high performance products. A similar manufacturing process described in this work, the Integrated Manufactured Board, is environmentally benign as the production of residuals is small [1–6]. Chalmers University of Technology has also made some research work in this area and is currently manufacturing modules that use a planar structure [7–9].

No environmental assessment has been made of similar manufacturing processes and the purpose of this paper is to assess the environmental impact for the process used by Chalmers to manufacture an electronic product using the SIP technology. The environmental assessment is partly made using a previously developed data collection model for the life cycle inventory of electronic products [10].

1 LCA Methodology of Electronic Products

A model for collection of life cycle inventory (LCI) data occurring in the upstream processes has been developed and the LCA software EcoLab has been used. [11,12]. The 45 LCI modules in **Fig. 1** were mapped against the SIP product parts list and only five modules could be found. The LCP substrate corresponds to the plastic mechanics module (group 19) within the mechanical components, the resistance material to resistors (group 32) within the passive components, the gallium arsenide (GaAs) bare die to the Standard IC (group 24), the copper laminate to metallic mechanics (group 20) and the conductive adhesive to composite mechanics (group 21).

The subgroups shown in Fig. 1 are: 1. Display units, 2. Diodes 3. Indicators, 4. Opto couplers, 5. Thyristors, 6. Transistors, 7. Component holders, 8. Connectors, 9. Fuses, 10. Relays, 11. Switches, 12. Microphones, 13. Loudspeakers, 14. Inductors, 15. Chokes, 16. Thread spirals, 17. Transformers, 18. Coil formers, 19. Plastic mechanics, 20. Metallic mechanics, 21. Composite mechanics, 22. Printed wiring boards, 23. Cables, 24. Standard ICs, 25. ASICs, 26. Metallised paper capacitors, 27. Metallised plastic capacitors, 28. Ceramic capacitors, 29. Electrolytic capacitors, 30. Large capacitors, 31. Potentiometers, 32. Resistors, 33. Resistor networks, 34. Varistors, 35. Thermistors, 36. Ferrite rods, 37. Delay lines, 38. Quartz crystal units, 39. Oscillators, 40. Adaption units, 41. Flexible disks, 42. Lamp panels, 43. Batteries, 44. Buzzers, 45. Antennas.

For a further explanation on the data collection model for LCI of electronic products, see [10]. A material content declaration of the switch is shown in **Table 1**.

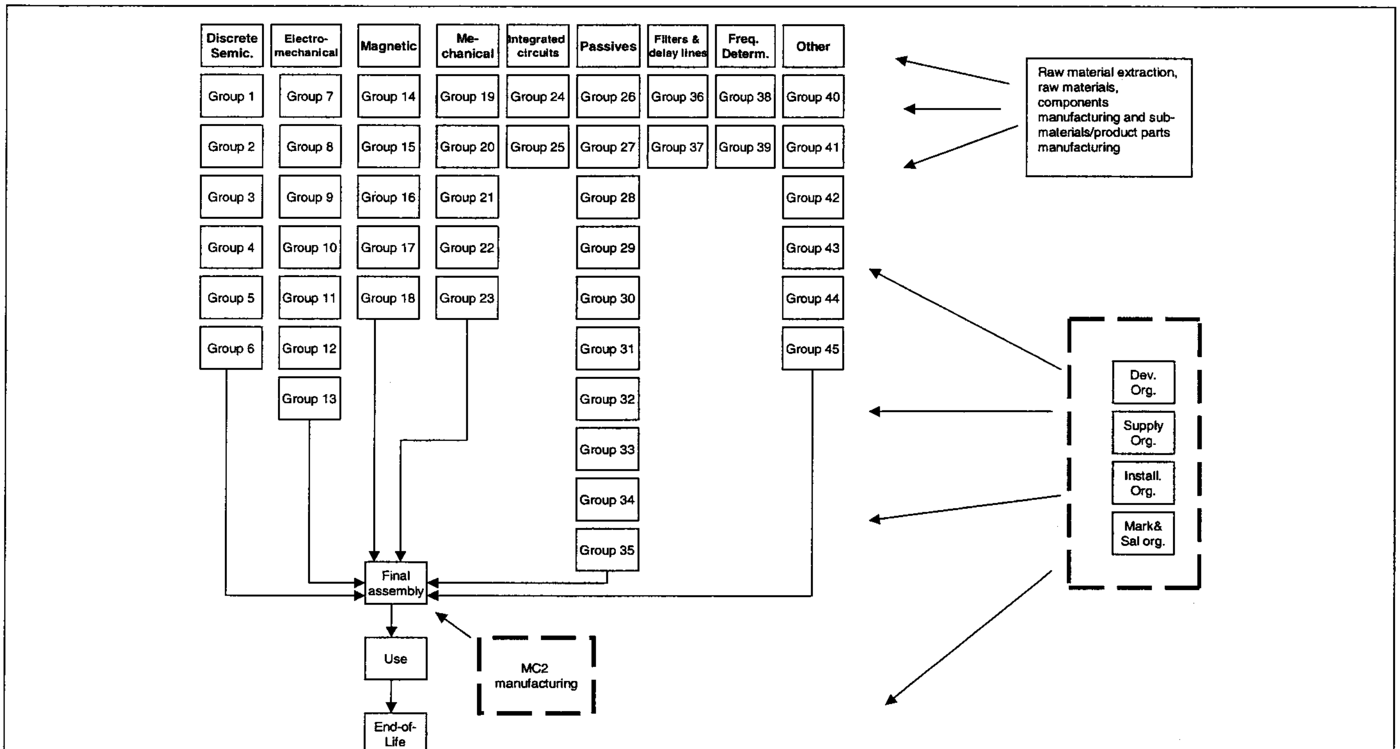

Fig. 1: The LCI data collection model and the schematic life cycle of an electronic product applied to the SIP GaAs MMIC Switch Product based on the LCP substrate

Table 1: The approximate material content declaration of the GaAs switch

Name of the part	Mass [g]	Material
LCP Substrate	0.158	LCP 50%, Glass fibre 50%
Conductive adhesive	0.25	Silver 80%, Diglycyl ether of bisphenol A 14%, 1-cyanoethyl-2-ethyl-4-methylimidazole 4%
GaAs bare die	0.00042	Gallium 50%, Arsenic 50%
Deposited resistance material	0.041	Nickel 60%, Chromium 40%
Copper laminate	0.281	Copper 100%
Deposited copper	0.0446	Copper 100%

2 System Boundaries and Data Collection

The system boundaries are set as the manufacturing processes which occur inside MC2 and the processes which could be found upstream directly connected to the materials and components which constituted the gallium arsenide (GaAs) switch. The scope is shown in **Fig. 2**.

Each of the process steps was analysed and, where possible, the materials used were followed to the cradle and thereby some of the possible environmental loads could be identified. The electricity consumption for each process step was also estimated. In **Table 2**, a material balance for the processes within MC2 is shown.

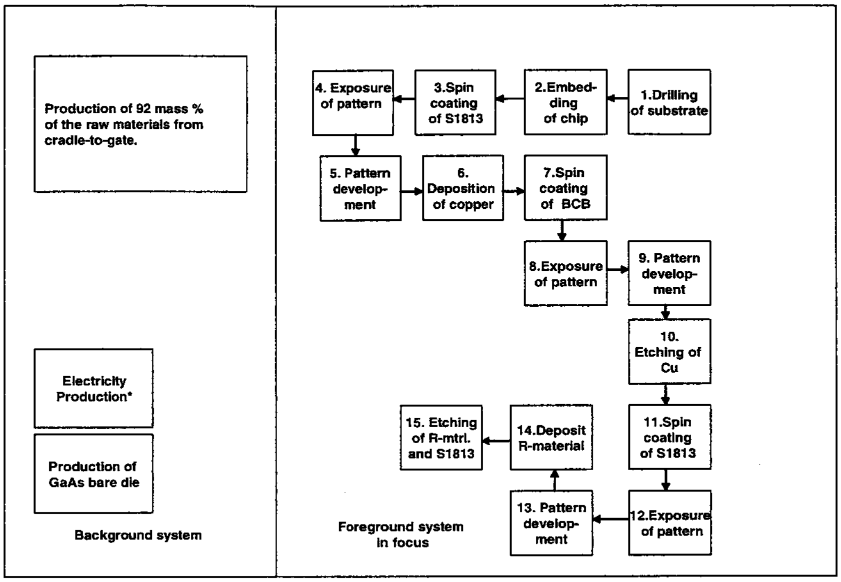

Fig. 2: The scope of the study. *The electricity consumption is only included for the 15 foreground processes and raw materials, and not for clean rooms

Table 2: Material balance for ancillary chemicals used in MC2

Substance	Category	Input(I)/Output(O)	Impact on	Quantity	Unit
Electricity	Energy	I	Technosphere	13.30	MJ
Cyclotene 3022-35	Raw material	I	Technosphere	3.15	g
Glass mask	Raw material	I	Technosphere	150	g
LCP glass fibre composite	Raw material	I	Technosphere	0.158	g
Acetone	Raw Material	I	Technosphere	475	g
Conductive adhesive	Raw Material	I	Technosphere	0.25	g
Cu	Raw Material	I	Technosphere	4.75	g
Deionised Water	Raw Material	I	Technosphere	4016	g
DS3000 Developer	Raw Material	I	Technosphere	17.2	g
Etching chemicals	Raw Material	I	Technosphere	20	g
Gallium Arsenide chip	Raw Material	I	Technosphere	0.000421	g
Methanol	Raw Material	I	Technosphere	238	g
MF319 Developer	Raw Material	I	Technosphere	39.1	g
Nickel/Chromium	Raw Material	I	Technosphere	4.10	g
Shipley S1112A Stripper	Raw Material	I	Technosphere	20	g
Shipley S1813 Photo-resist	Raw Material	I	Technosphere	6.55	g
GaAs switch	Product	O	Technosphere	0.749	g
1,2-Dihydro-2,2,4-trimethyl quinoline	Emission	O	Air	2.05	g
Mesitylene	Emission	O	Air	0.123	g
Acetone	Emission	O	Water	475	g
Cr	Emission	O	Water	0.00293	g
Cu	Emission	O	Water	0.01	g
Deionised Water	Emission	O	Water	4016	g
Divinylsiloxane bis(benzocyclobutene)	Emission	O	Water	0.000901	g
DS3000 Developer	Emission	O	Water	17.2	g
Methanol	Emission	O	Water	238	g
MF319 Developer	Emission	O	Water	39.1	g
Ni	Emission	O	Water	0.00439	g
Shipley S1112A Stripper	Emission	O	Water	20	g
Cu	Waste	O	Technosphere	4.42	g
Cyclotene 3022-35	Waste	O	Technosphere	0.98	g
Etching chemicals	Waste	O	Technosphere	20	g
Glass mask	Waste	O	Technosphere	150	g
LCP glass fibre composite	Waste	O	Technosphere	0.000237	g
Nickel/Chromium	Waste	O	Technosphere	4.06	g
Shipley S1813 Photo-resist	Waste	O	Technosphere	6.56	g

3 Description of Manufacturing Processes Inside MC2

3.1 Manufacturing process

The manufacturing processes are clearly shown in Fig. 2. At first, a hole was laser drilled through an LCP laminate. The switch chip was installed into the hole using conductive adhesive (ICA). Next, the lithography process of S1813 was performed to open the interconnections of the chip, followed by the copper deposition. Then, another lithography process of BCB was done to define the circuit pattern. Then, the copper was etched away without being covered by BCB. Finally, the lithography process of S1813 was done once more to define the bias resistor pattern. The resistance material was deposited by an AVAC evaporation system followed by the stripping process of S1813, to fabricate the bias resistor.

3.2 Materials and equipment used in the manufacturing processes

The embedded switch chip is a GaAs MMIC from Alpha. A Gore-Tex LCP laminate with a size of 3 cm x 3 cm and with a thickness of 125 µm is used as a substrate. The glue to fix the chip is Isotropic Conductive Adhesive (ICA), which by mass consisted of 80% Ag, 14% diglycyl ether of bisphenol A and 4% 1-cyanoethyl-2-ethyl-4-metylimidazole [13,14]. The resistance material is nickel (Ni)/chromium (Cr) alloy (60% Ni and 40% Cr by mass) from MC2 [15].

The photoresist S1813 from Shipley mainly consists of 2-methoxy-1-methyl-ethyl acetate [16,17]. In the lithography process of S1813, the developer is MF319 from Shipley, which mainly consists of non-hazardous ingredients (95%) and tetramethylammonium hydroxide up to 5% [18]. The remover S1112A from Shipley [19], which consisted of 28% diethylene glycol N-butyl ether by mass, 27% 2-butoxy ethanol, 16% 2-amino-ethanol 14% dipropylene glycol methyl ether, 14% non-hazardous ingredients and 1% furfuryl alcohol was used in the stripping process of S1813.

The BCB photoresist, Cyclotene 3022-55 from Dow Chemical, consists of 65% 1,2-dihydro-2,2,4-trimethyl quinoline by mass, 29% divinylsiloxane bis(benzocyclobutene) (BCB) and up to 6% mesitylene [20–22]. The chemical used for pattern development, DS3000 from Dow, mainly consists of 1,3,5-tris(1-methylethyl)-benzene [23].

In the manufacturing processes, the spin-coating machine was used to spin off the photoresists. The mask aligner from Karl Suss [24] was used to perform UV-exposure of the photoresists. Heat plates were used to bake the SIP module in the lithography processes. Copper and nickel/chromium metals were deposited in a high vacuum thin film vapour deposition system (AVAC HVC 600).

4 Results

All results are presented per gallium arsenide (GaAs) Monolithic Microwave Integrated Circuit (MMIC) Switch Product (denoted switch in diagrams).

The results have been calculated by multiplying the characterisation indexes of different resources with the amounts consumed in the life cycle. The unit of the characterisation index is 1/year as it is defined as the annual global consumption divided by the amount of known global reserves of the resource. The individual indices have been calculated using data from USGS [25] where the figure for Mine production was divided by the figure for Reserves. Hence, the unit of the y-axis in **Fig. 3** is given in g/year.

The amounts of all identified gases contributing to the greenhouse warming, for those in which a characterisation index was available, is represented by EcoLab multiplied by its

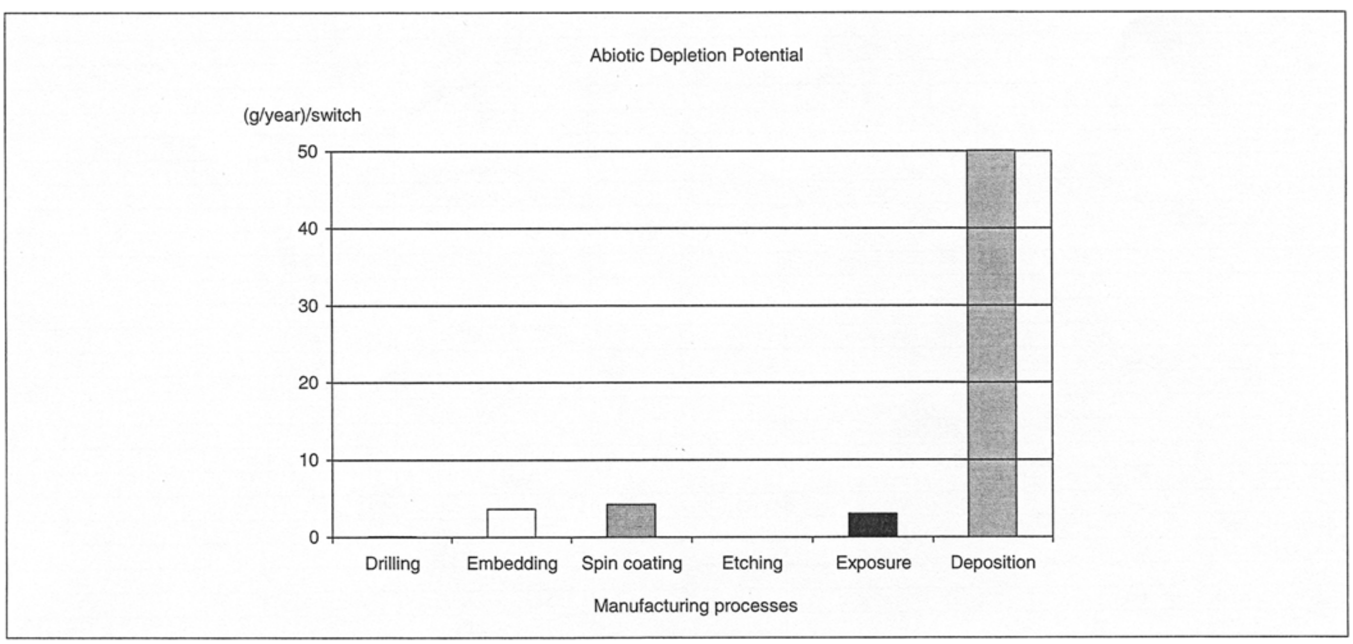

Fig. 3: Abiotic Depletion Potential (ADP) for different manufacturing processes

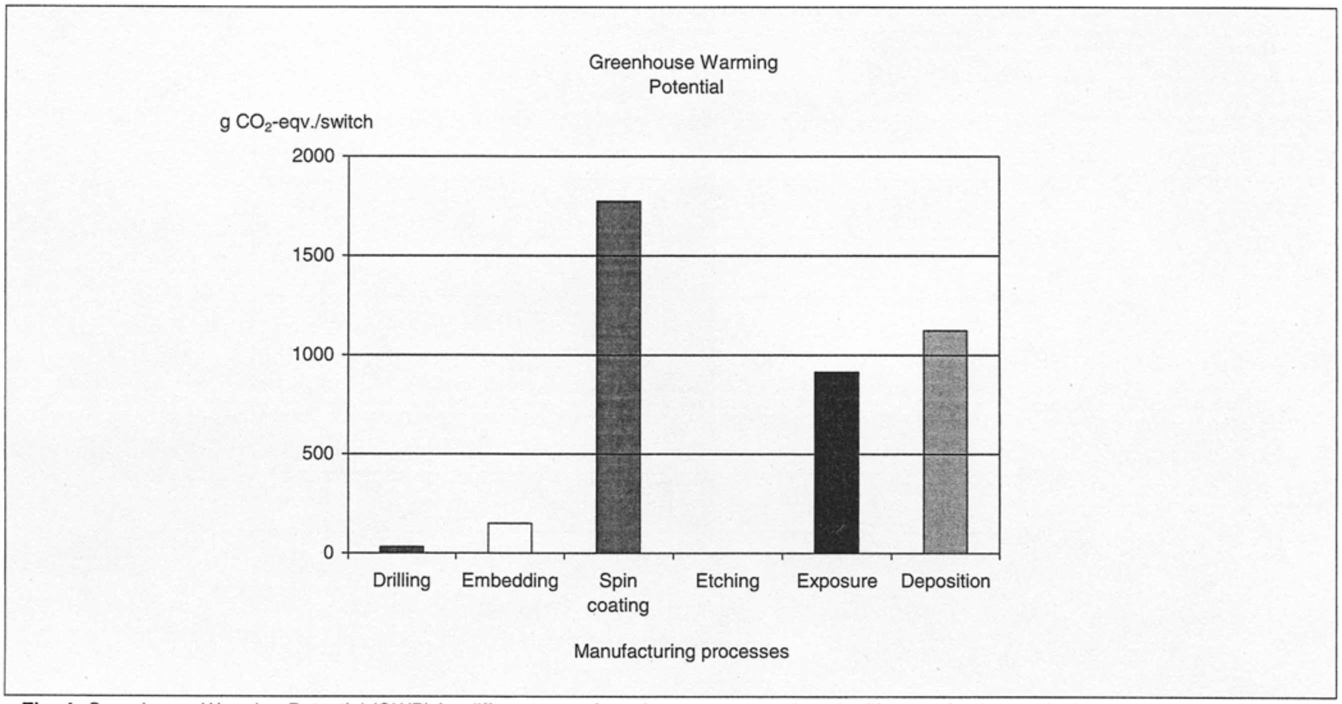

Fig. 4: Greenhouse Warming Potential (GWP) for different manufacturing processes, when the life span for the gas in the atmosphere is 100 years

respective index. Hence, the unit of the y-axis in **Fig. 4** is given in g CO_2-equivalents.

The amounts of all identified materials contributing to the weighting method, for those in which a weighting index was available [26], is represented by EcoLab multiplied by its respective index. Hence, the unit of the y-axis in **Fig. 5** is given in millipoints.

Palladium contributes to 100% in the spin coating bar in **Fig. 6** and copper ore to 100% for deposition. The amounts of all identified resources and emissions contributing to the weighting method EPS, for those which an environmental load index (ELI) was available [27], is represented by EcoLab multiplied by its respective index. Hence, the unit of the y-axis in Fig. 6 is given in Environmental Load Units (ELU).

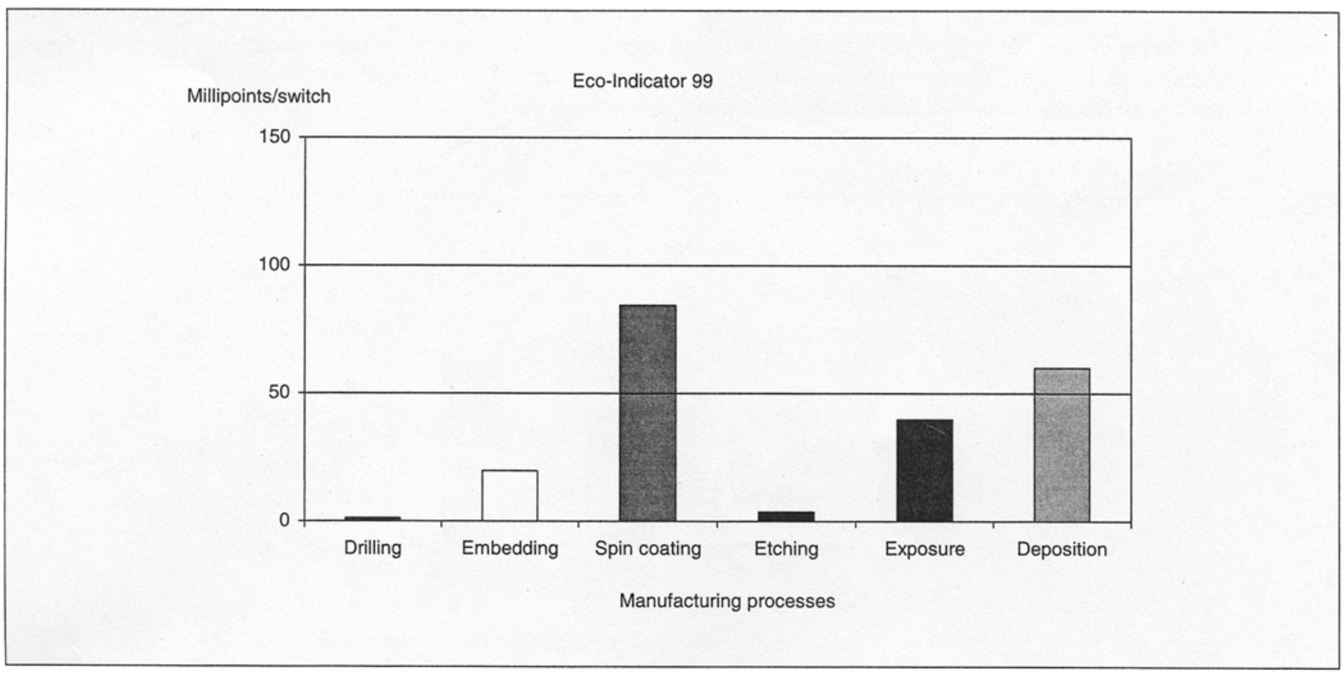

Fig. 5: Eco-Indicator 99 results for different manufacturing processes

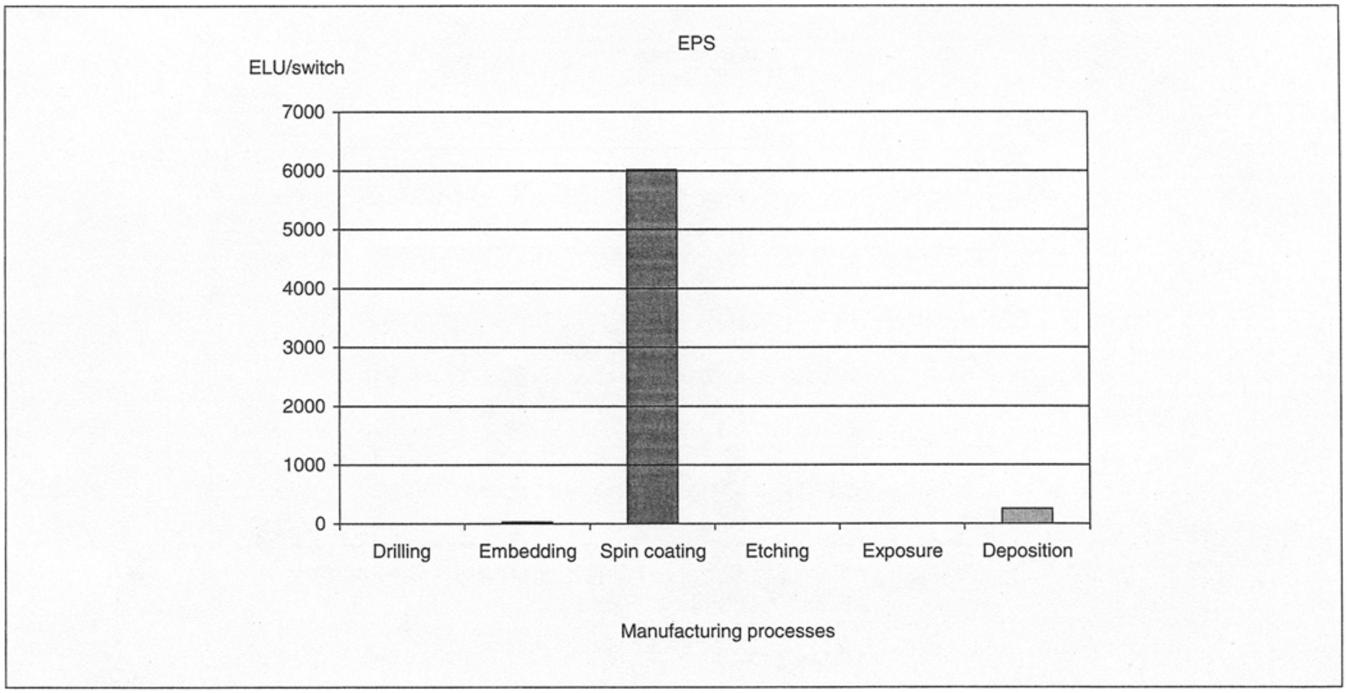

Fig. 6: EPS results for different manufacturing processes

5 Discussion

The results imply that the three spin coating steps as well as the two deposition steps and their associated upstream environmental impacts are of highest concern. The uncertainty is estimated to be small enough to be able to draw conclusions as the most important unit operations within the system boundaries were included.

Within the system boundaries, a number of materials were identified needed to produce e.g. Shipley S1813 Photoresist, for example 2-methoxy-1-methyl-ethyl acetate. However, it was not possible to obtain LCI data describing the production of 2-methoxy-1-methyl-ethyl acetate and some other materials used in the upstream processes. A calculation was made where 123 possible unit processes within the product system were identified. Eco-profiles were available for 37 unit processes. Inside the EcoLab software, an estimated electricity consumption of 1 MJ/kg, 5 MJ/kg and 10 MJ/kg was added in turn to 86 'new' identified unit processes for which no LCI data was available. The electricity consumptions used could be underestimated for the gallium arsenide bare die manufacturing chain as semiconductor grade chemicals require a higher degree of purity than elsewhere [28]. As shown in **Fig. 7**, this sensitivity calculation resulted in no significant changes to the overall result.

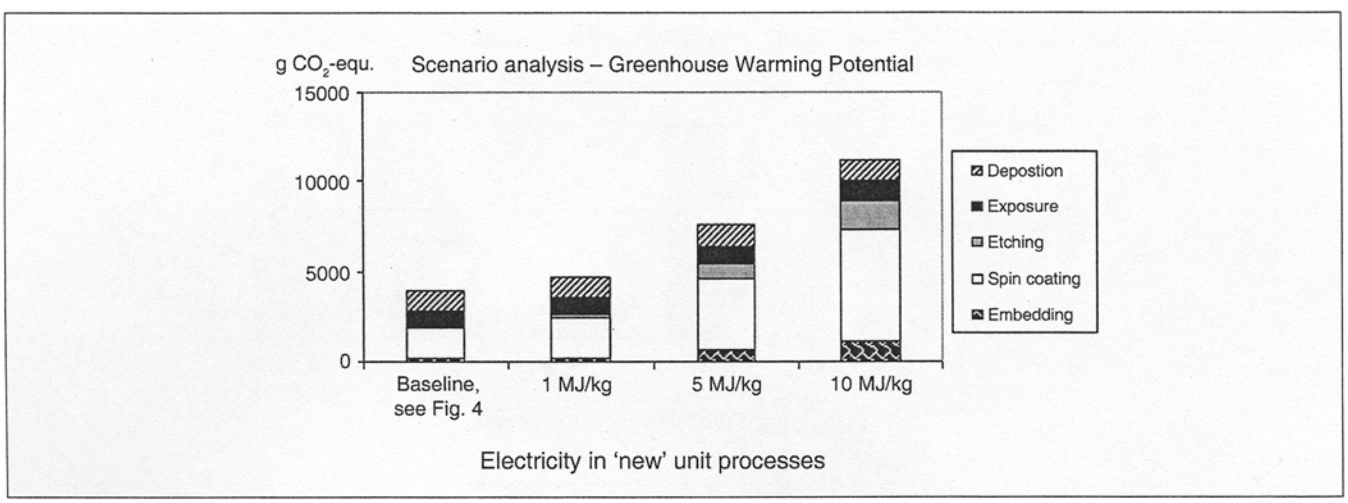

Fig. 7: Result of different electricity consumption scenarios in upstream unit processes

The impact due to electricity production is most important for the overall results and the LCI data used for electricity production corresponds well with the Eco-Indicator 99 value for European average electricity production (6.1 millipoints/MJ) including fuel production [29]. The LCI data availability is good within the system boundaries, although the only primary data collected was from the foreground system. For 92 mass% of the ingoing raw materials (e.g. acetone and copper) LCI data was covered, but only 16% would be covered if deionised water production were to be included. In the background system, the manufacturing process for silicon bare dies was used to model the gallium arsenide bare die. This might be an underestimated environmental aspect as gallium arsenide has a more complex manufacturing process overall than does silicon [30].

The characterisation index coverage is as follows: ADP indices were found for 77 mass% of the resources (water resources are excluded as no ADP index could be found). GWP indices were found for 39 mass% of the gases emitted to air. For some gases, e.g. radioactive emissions, the greenhouse warming potential may be very low or does not physically exist, and the coverage value would be much higher. The coverage of weighting indices is 51 mass% for Eco-Indicator 99 (99.9 mass% for emissions to air, 0.003 mass% for emission to water and 76 mass% for resources). For EPS, the coverage is 45 mass% (39 mass% for emissions to air, 0.02 mass% for emission to water and 76% for resources). Water resources are excluded for both Eco99 and EPS. The most important index data gaps for Eco-Indicator 99 is judged to be emissions of acetone and methanol to water and for EPS lignite resources and radioactive emissions to air. More research needs to be done in developing new weighting indices, especially indices for the emissions to water and resource depletion. No transportation environmental impacts are included in the modelling, but they usually have a small impact compared, for example, to electricity production [31]. The Fraunhofer Institute in Germany have developed a method called Toxic Potential Indicator (TPI) which evaluates the potential toxicity of the product material content and the ProTox model evaluates toxicity of materials used to manufacture the product [32,33]. TPI-values for 86 mass% were found for the materials in the product content (see Table 1) and the highest toxicity originates from the silver in the isotropic conductive adhesive (ICA). TPI-values for 91 mass% of raw materials used in the MC2 manufacturing process including upstream processes were found and methanol contributes to 91% followed by 6% from acetone. Other process materials with toxicity, such as alpha-chloro-orto-xylene, which is one of the starting points of Cyclotene 3022-55, could have an impact. Another example is from the material safety data sheet of Cyclotene 3022-55 from Dow, which indicates that mesitylene is slightly toxic to aquatic organisms. An environmental advantage from an environmental/safety/health point of view is that the LCP substrate does not contain any brominated flame retardants or nitrogen, and on the basis of the material itself, no hydrogen bromide or nitrous gases would be formed when incinerating the polymer. A comparison (based on material content declaration) between an old electronic product, a digital telephone, which weighs 1100 g, and the new manufactured switch, which weighs approximately 0.7 g, shows that the telephone has a total TPI-value of 255 900, i.e. 233 TPI/g and the switch has a TPI-value of 12800/g. These two products provide different functions, but they still provide an indication of the toxicity of future electronics. This could be interesting, especially if System In-a-Package (SIP) would be used in smart cards, which will be much more frequent in the future society. Before spin coating, you need to heat the substrate to remove the water on the surface, which is partly why electricity is consumed here. Another explanation for the rather high impact of spin coating is the acetone used. It was not possible to compare the results using other environmental assessment models due to the lack of information. It is useful to perform the environmental assessment in the manner described above as the same could be done for the competing packaging concept System-on-a-Chip (SOC) without having to expand the system boundaries. As clean room environments are needed to produce both SIP and SOC products, it is not necessary to include it in future calculations. For the weighting method Eco-Indicator 99, the result mostly reflects the acetone and methanol consumption within spin coating and the electricity production dominates for deposition and exposure processes. For the weighting method EPS, palladium acetate, which is used as a catalyst in the manufacturing process of divinylsiloxane bis(benzocyclobutene), which in turn is used to manufacture Cyclotene 3022-55, which in turn is spin coated, dominates totally.

6 Conclusions

The following conclusions are based on results from potential global warming and resource depletion. The reasons for choosing these categories are that these impact categories can be quantified without large methodological difficulties, which is not the case for other categories.

- The electricity consumption of the deposition machine and the solvent consumption in spin coating are the two most important environmental aspects.
- For the environmental impact category abiotic depletion potential (ADP), the result mainly reflects the copper consumption in the copper deposition process.
- For the environmental impact category greenhouse warming potential (GWP), the result is mainly due to acetone production from cradle-to-gate as acetone is used as a solvent in spin coating. For the two deposition processes, the electricity production dominates over material production.

7 Recommendations and Outlook

It is recommended to search for more accurate LCI data for the ingoing unit processes and develop more characterisation and weighting indices to see if the conclusions would change. It should be analysed if other, simpler or more advanced, environmental assessment methodologies would provide different results than the method described in this paper. More studies should be made on how the machines are used for a longer period in the MC2 factory in order to see if this influences the results. If possible, the copper and nickel/chromium waste should be recycled in connection with

the deposition processes. On a wider perspective, different packaging concepts for microsystems should be evaluated. A calculation should be made using the indicators in Eco-Indicator 99 for material production from cradle-to-gate for such materials as triisopropyl benzene, which is a part of the pattern developer DS3000, in order to see if the overall results would change.

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